Smilei)

3rd Smilei user & training workshop

9-11 March 2022

Numerical investigation of high-energy photon emission in double-layer targets with particle-in-cell codes

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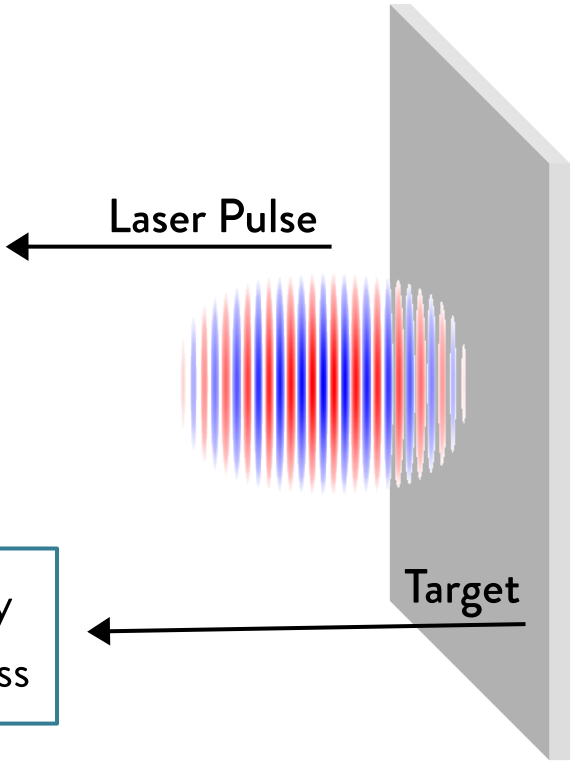
Laser-Plasma Interaction with Solid Targets

- fs duration
- focal spot of μm
- I > 10^{18} W/cm^2

$$a_0 = \frac{eE_0}{m_e \omega c} > 1$$



- Solid density
- μm thickness

- Standard for Laser Driven Ion Acceleration
- Interesting also for other types of radiation
- But can we enhance the coupling with the laser? Yes!

↓

Advanced Targets

Fedeli, L., Formenti, A., Cialfi, L., Sgattoni, A., Cantono, G., & Passoni, M. (2017). Structured targets for advanced laser-driven sources. Plasma Physics and Controlled Fusion, 60(1), 014013.

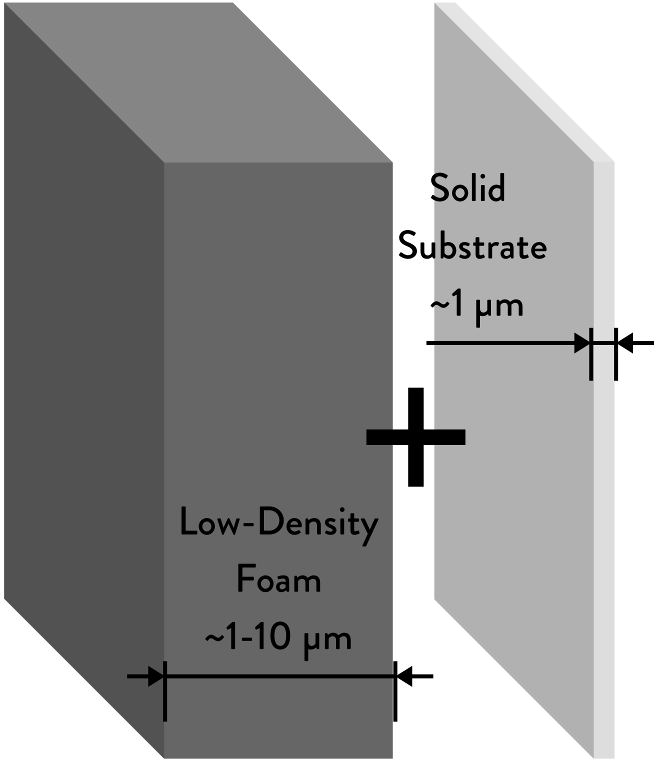
... and with Double-Layer Targets (DLTs)

$$n_c = \frac{m_e \omega^2}{4\pi e^2}$$

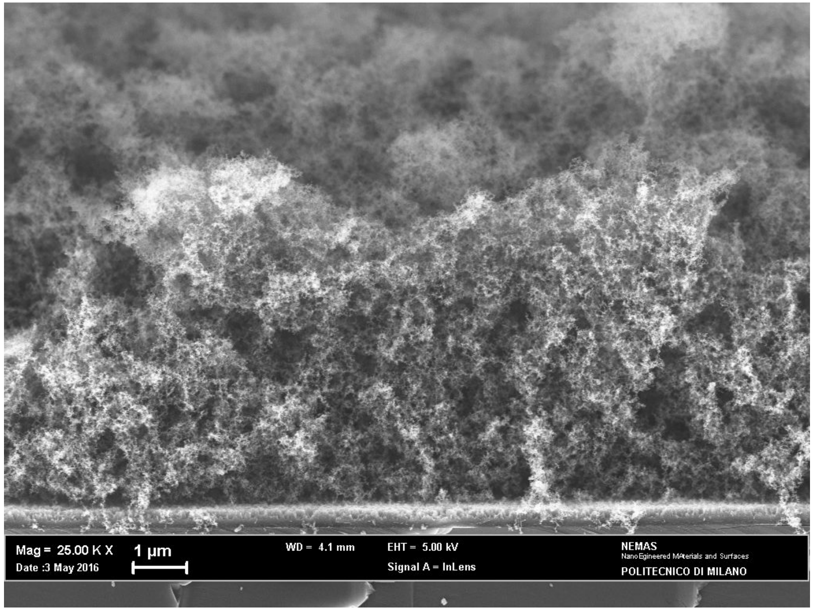
Near-Critical
Electron
Density

↕

Density
of few mg/cm^3



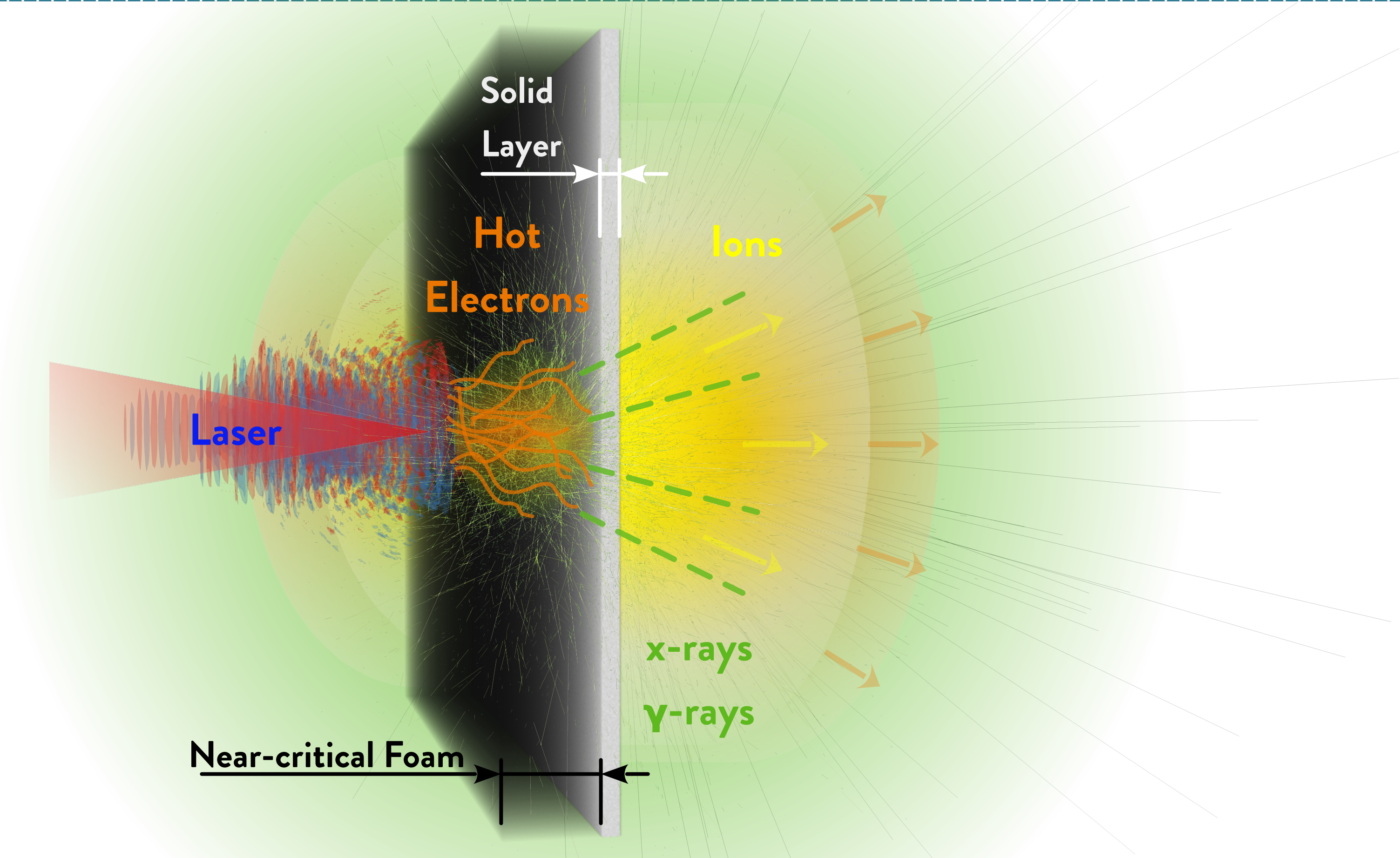
Carbon Foam on **Aluminum** Substrate



Produced with **Pulsed Laser Deposition** (PLD)

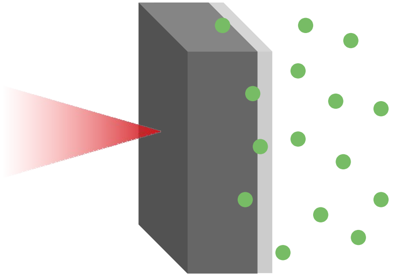
Maffini, A., Pazzaglia, A., Dellasega, D., Russo, V., & Passoni, M. (2019). Growth dynamics of pulsed laser deposited nanofoams. Phys. Rev. Materials, 3, 083404.

… and with Double-Layer Targets (DLTs)



High-Energy Photon Emission

Enhanced Acceleration of Electrons in Foam + Dense Substrate



Emission of **High-Energy Photons** (keV-MeV) by Electrons

Non-Linear Inverse Compton Scattering (NICS)

Scattering in the electromagnetic fields and head-on collision with the reflected laser pulse

Bremsstrahlung

Scattering in the Coulomb field of nuclei inside the target
Improved by mm-thick high-Z substrate!

Motivations of Research

Interests

Tunable Laser-Driven High-Energy Photon Sources

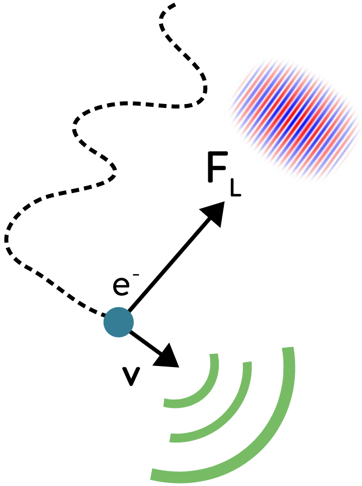
Technological Applications and Fundamental Physics Studies:

Radiography, Tomography, Interrogation of Materials, Diagnostic for laser-plasma, QED regime exploration

Challenges

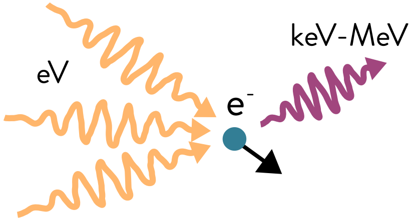
- **Simulations** are fundamental but must be critically used
- Novelty of **non-conventional targets**

Non-linear Inverse Compton Scattering (NICS)



Electron feeling the Lorentz Force due to the presence of Strong Fields

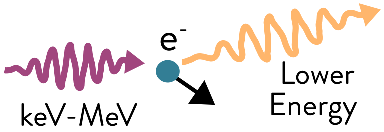
NICS



Non-linear! $a_0 = \frac{eE_0}{m_e \omega c} \gg 1$

Inverse!

Compton Scattering



Electron Quantum Parameter χ

$$\chi = \frac{\gamma}{E_s}\sqrt{\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right)^2 - \left(\frac{\mathbf{E} \cdot \mathbf{v}}{c}\right)^2}$$

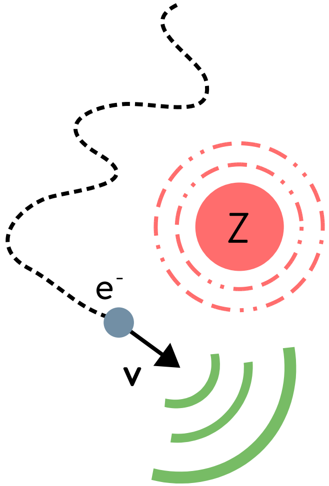
Maximized in electron head-on collision with the laser pulse!

Quantum Effects $\chi \sim 1$

- discrete emission with maximum energy
- quantization of the motion of the electron

Lorentz Factor $\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$ Schwinger Field $E_s = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18} V/m$

Bremsstrahlung



Electron scattering in the Coulomb Field of a Target Nuclei

- relativistic description
- quantization of the motion of the electron in the Coulomb field
- screening from electrons around the nucleus
- electron-electron bremsstrahlung

Simple Cross-Section Form

$$\frac{d\sigma}{d(\hbar\omega)} = \frac{Z^2}{\beta^2}\frac{1}{\hbar\omega}\Sigma(Z, E, \kappa)$$

$\beta = v/c \qquad \kappa = \hbar\omega/E$

E → Electron Kinetic Energy

Several cross-sections available:

- Seltzer-Berger (tabulated)
- Bethe-Heitler (analytic)
- ...

Koch, H. W. & Motz, J. W. (1959). Bremsstrahlung Cross-Section Formulas and Related Data. Rev. Mod. Phys., 31, 920–955.

Methods: Monte Carlo inside Particle-In-Cell (PIC)

Evaluation of High-Energy Photon Emission and Radiation Reaction at PIC simulation run-time

- Time interval between two emission events given by a non-homogeneous exponential distribution with time-dependent **Rate of Photon Emission**

$$p(t) = \lambda(t) e^{-\tau(t)} \quad \lambda(t) = dN/dt \quad \tau(t) = \int_0^t \lambda(t')dt'$$

NICS

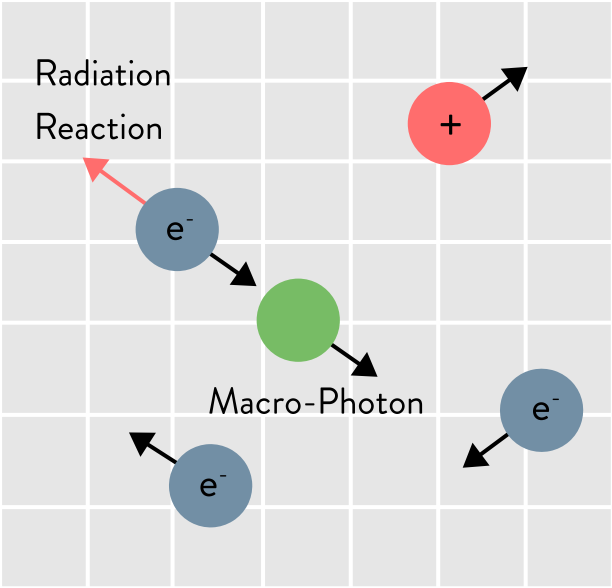
$$\frac{dN}{dt} = \frac{\sqrt{3}}{2\pi} \frac{e^2 m_e c}{\hbar^2} \frac{\chi}{\gamma} \int_0^{+\infty} \frac{F(\omega,\chi)}{\omega} d\omega$$

Bremsstrahlung

$$\frac{dN}{dt} = n_i \sigma v$$

- Sampling of **Photon Energy** and **Back-Reaction**

$$\mathbf{p}_{ph} = \frac{\hbar\omega}{pc}\mathbf{p} \qquad \mathbf{p}^f = \left(1 - \frac{\hbar\omega}{pc}\right)\mathbf{p}$$



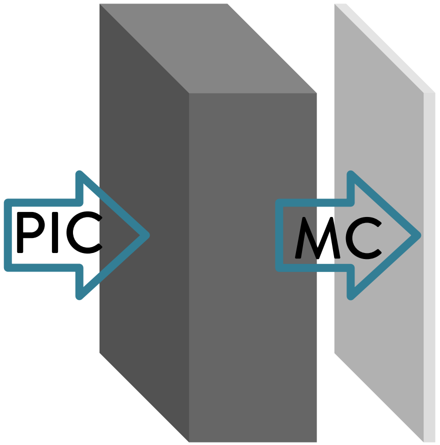
Dual Treatment of Electromagnetic Radiation !!

Gonoskov, A. et al. (2015). Extended particle-in-cell schemes for physics in ultrastrong laser fields: Review and developments. Phys. Rev. E, 92, 023305.

Methods: Alternatives

Evaluation of High-Energy Photon Emission after PIC simulation

- Feed a **standard Monte Carlo** code with the electron distribution computed by the PIC. Easy for bremsstrahlung in DLTs or with a converter.



- **Analytic estimations** for NICS and Bremsstrahlung

Methods: SMILEI 2D Simulations with NICS in DLTs

Smilei)

Carrying on

Caprani, R. Compact photon sources in multi-PetaWatt facilities: a kinetic numerical investigation. (2020) M.Sc. Thesis

GALILEO
CINECA

General properties	
Box size (x, y)	(Variable, 40.96 μm)
Points per λ (x, y)	(50, 50)
CFL	0.95
Duration	Variable
Processing units	144
Boris pusher, Silver-Muller in x, Periodic in y, Load balancing, Fully Ionized	

Target Properties	
Homogeneous Foam (Z, A)	(6, 12)
PPC e^-	Variable <10
Substrate (Z, A)	(13, 27)
Density	450 n_c
PPC e^-	32
Thickness	2 μm
+ **Contaminants**	

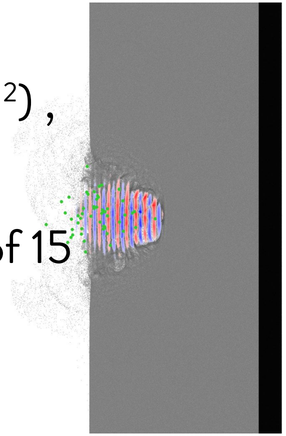
Laser Properties	
Wavelength λ	0.8 μm
Shape in space	Gaussian
Shape in time	$\cos^2$
Waist	3 μm
FWHM	20 fs
Angle of incidence	0°
Polarization	linear, in plane

MC Photon emission	
Minimum energy	128keV
Minimum χ	10^{-4}
Sampling	1 pho per e^-
Tables	Default

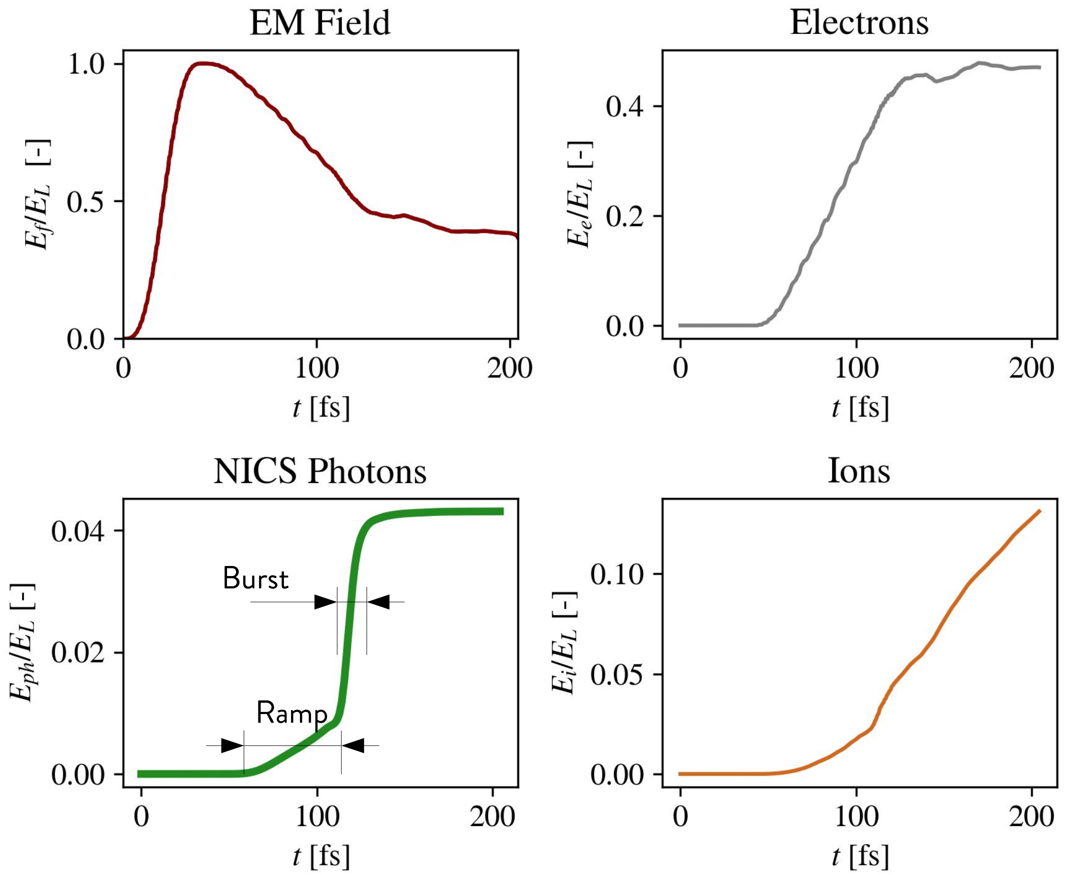
NICS in DLT

Simulation Parameters:

- Laser: a_0=50 (5.4x10^{21} W/cm^2) , waist 3 μm, FWHM=20 fs
- Homogeneous carbon foam of 15 μm and density 2 n_c
- Substrate of 2 μm of Al

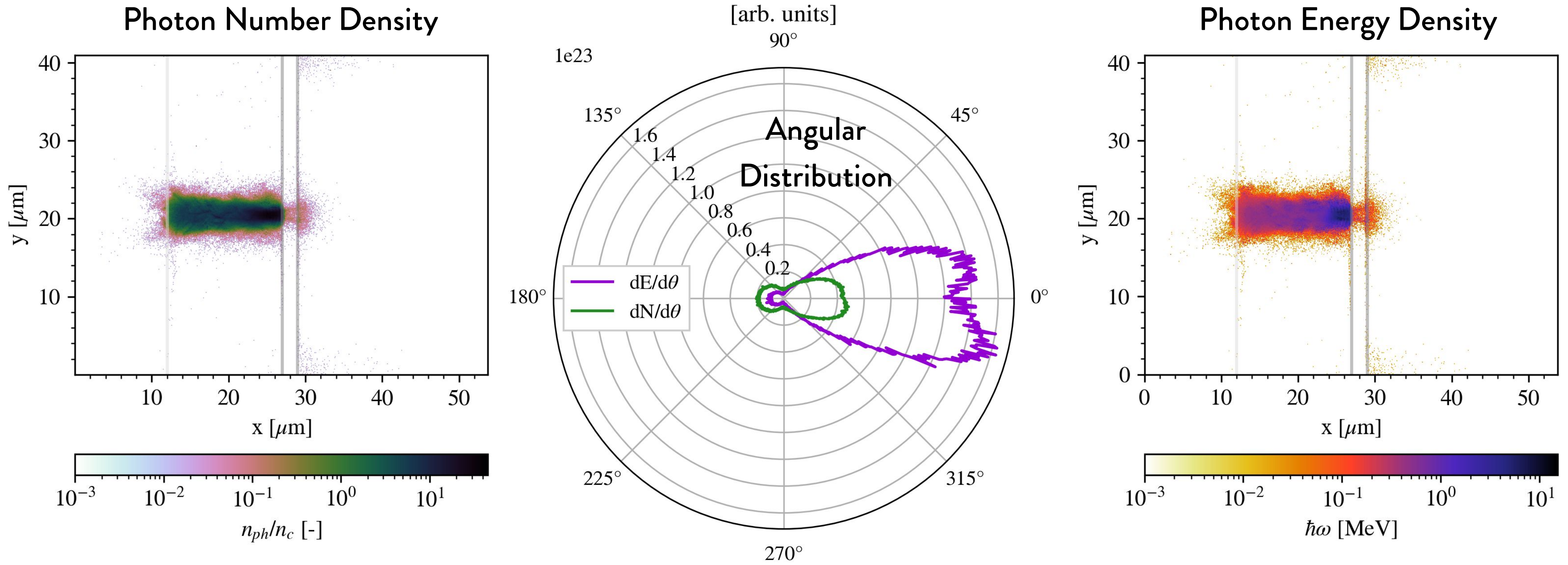


- 4 Channels involved in the Energy Exchange
- **2 Distinct Phases** of High-Energy Photon Emission



NICS in DLT - High-Energy Photons

- High-Energy Emission follows the Laser Pulse propagation and peaks in front of the substrate

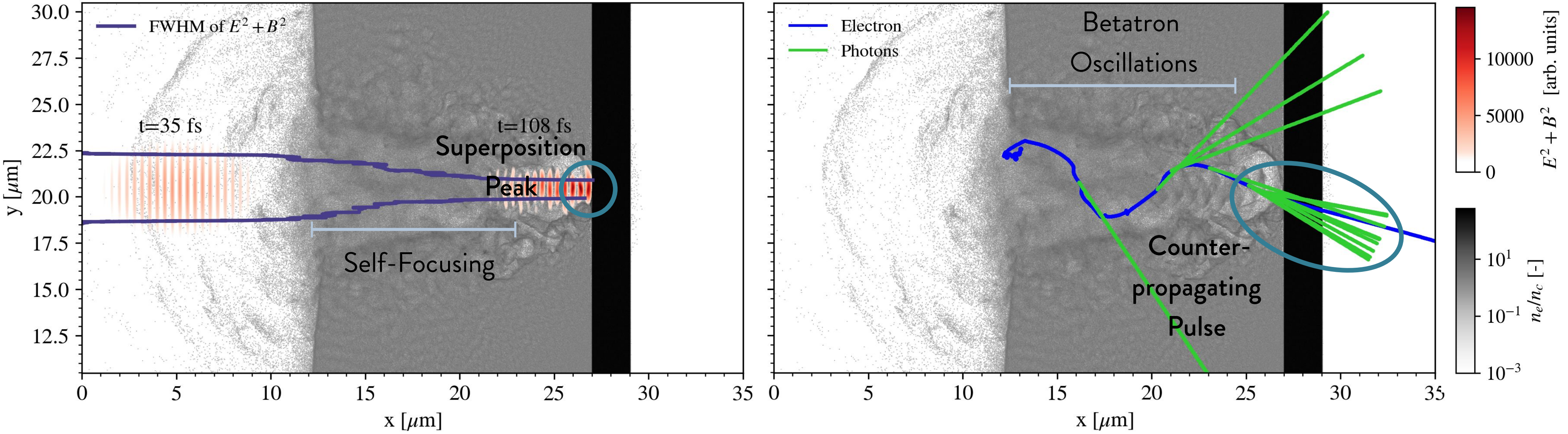


NICS in DLT – Fields and Electrons

- Relativistic Self-Focusing in Foam (optimal length)
- Superposition when reflecting on the Substrate

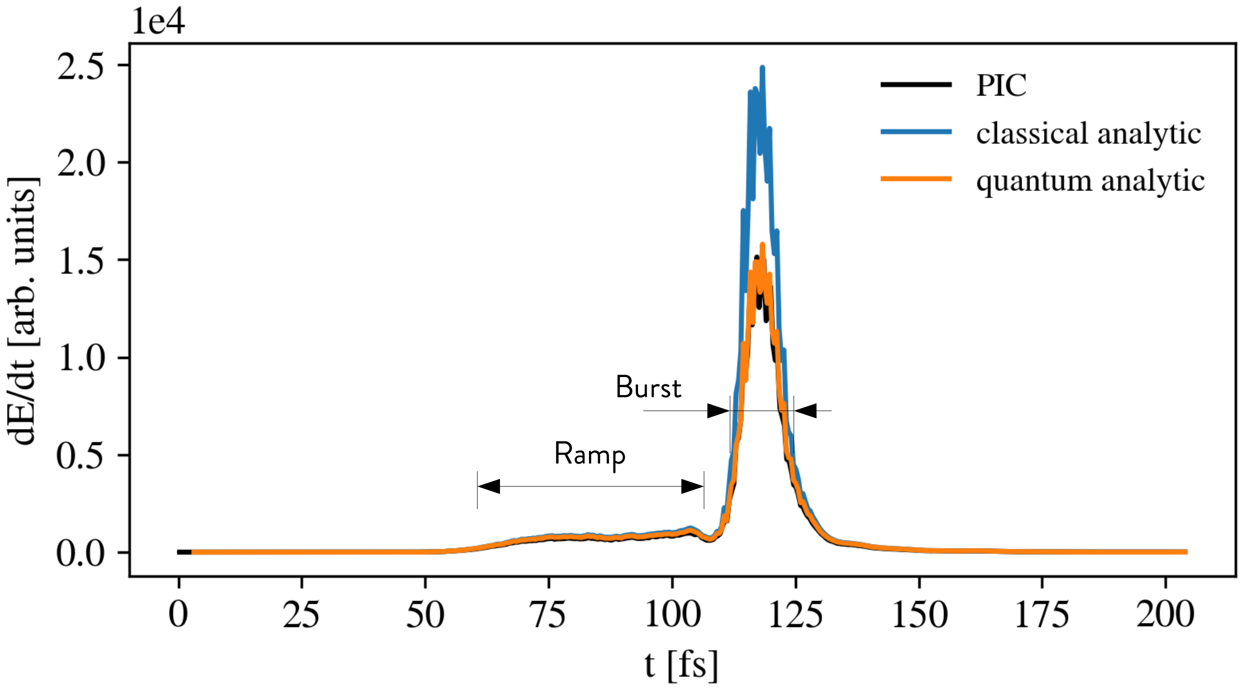
Ramp
Burst

- Direct Laser Acceleration of electrons and Transversal Oscillations
- Counter-propagation with the Pulse



Analytic estimations for NICS

Emitted Power in High-Energy Photons by all Electrons



Computed from Macro-Electrons

$$\frac{dE}{dt} = \frac{2\alpha m_e^2 c^4}{3\hbar} \sum_e \chi_e^2 g(\chi_e) w_e$$

Classical limit

$$g(\chi_e) = 1$$

With **quantum** effects

$$g(\chi_e) = \frac{9\sqrt{3}}{8\pi} \int_0^{+\infty} \left[\frac{2y^2 K_{\frac{5}{3}}(y)}{(2+3\chi_e y)^2} + \frac{36\chi_e^2 y^3 K_{\frac{2}{3}}(y)}{(2+3\chi_e y)^4} \right] dy$$

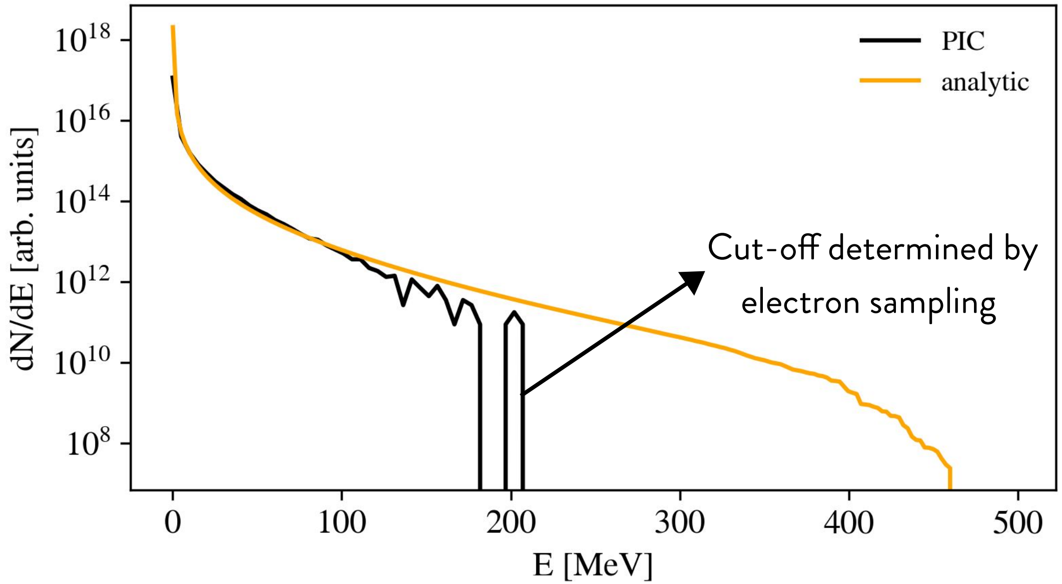
Analytic estimations for NICS

Spectrum in energy of all emitted Photons by Electrons

$$\frac{dN}{dE_p} = \int dt \int_{E_p}^{\infty} \left\{ \frac{dN}{dE_e} \frac{\alpha m_e c^2}{\sqrt{3}\pi\hbar\gamma(E_e - E_p)} \left[\frac{E_p^2}{E_e^2} K_{\frac{2}{3}}(y) + \left(1 - \frac{E_p}{E_e}\right) \int_y^{\infty} K_{\frac{5}{3}}(x) dx \right] \right\} dE_e$$

Computed from Macro-Electrons

$$y = \frac{2E_p}{3(E_e - E_p)\overline{\chi}(E_e)}$$

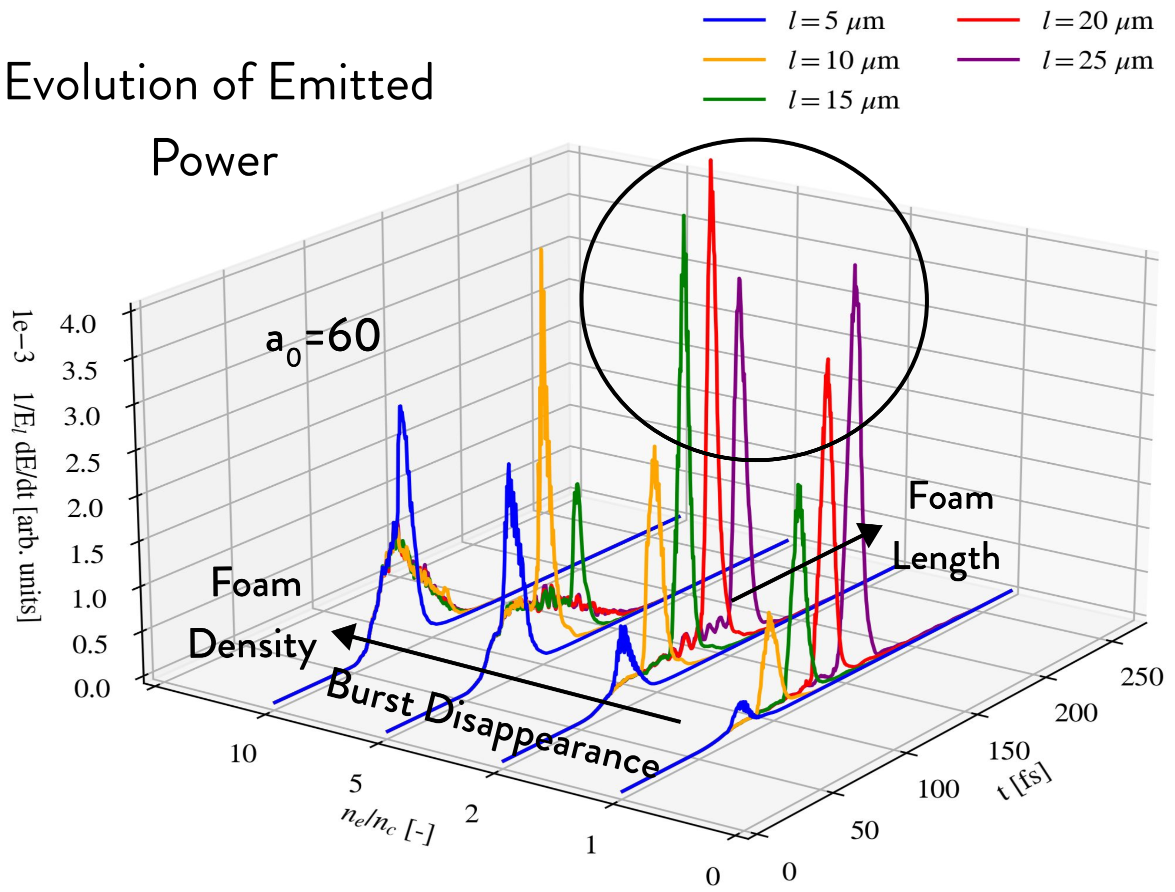


Impact of Target Parameters for NICS

- Higher power peak → foam length **slightly longer than the self-focusing length** $= \sqrt{\ln 2} w_0 \left(\frac{a_0 n_c}{n_e}\right)^{1/2}$
- Laser is absorbed at **high densities** → **no burst**
- Trend → **Low densities** (1-2 n_c) and **large foam thickness** (20-25 μm)

Changed Parameters:

- Foam densities: 1-2-5-10 n_c
- Foam length: 5-10-15-20-25 μm
- A_0: 20-40-50-**60** (0.9-3.5-5.4-7.**8x10²¹** W/cm²)



Methods: Bremsstrahlung Simulation

Bremsstrahlung modelling

Monte Carlo inside PIC

- **Mean-field** or **collisional** approach
- More **self-consistent** and realistic
- **Computational Challenges**:
  - ps duration
  - thick (1-10 mm) targets
  - solid densities (100-1000 n_c)

Required resources

Al Ti Ta W Au

Monte Carlo after PIC

- **Standard** mean-field approach.
- Thick targets → Yes!
- Neglects electron recirculation effects
- Need to think about PIC coupling.

GEANT4 A SIMULATION TOOLKIT

Most accurate collisional approach not available in open source code → Could be implemented in Smilei

Methods: Bremsstrahlung Simulation

EPOCH

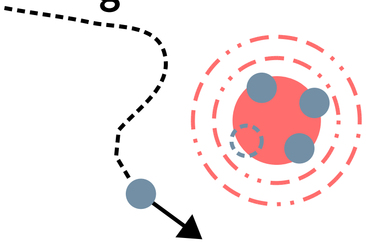
- **Averaging Approach** to Bremsstrahlung simulation

$$\frac{dN}{dt} = n_i \sigma v$$

no collisions among electrons and ions

Martinez, B., Lobet, M., Duclous, R., d'Humières, E., & Gremillet, L. (2019). High-energy radiation and pair production by Coulomb processes in particle-in-cell simulations. Physics of Plasmas, 26(10), 103109.

- **Screening Effects** not taken into account properly



Ionized Species in the Plasma

Seltzer-Berger tabulated cross-sections

Seltzer, S. M., & Berger, M. J. (1986). Bremsstrahlung energy spectra from electrons with kinetic energy 1 keV–10 GeV incident on screened nuclei and orbital electrons of neutral atoms with Z = 1–100. Atomic Data and Nuclear Data Tables, 35(3), 345–418.

- synthesis of various theoretical and experimental results
- range of electron energies: from electron rest energy up to 10 GeV
- atomic screening
- electron-electron bremsstrahlung

Bremsstrahlung in DLTs

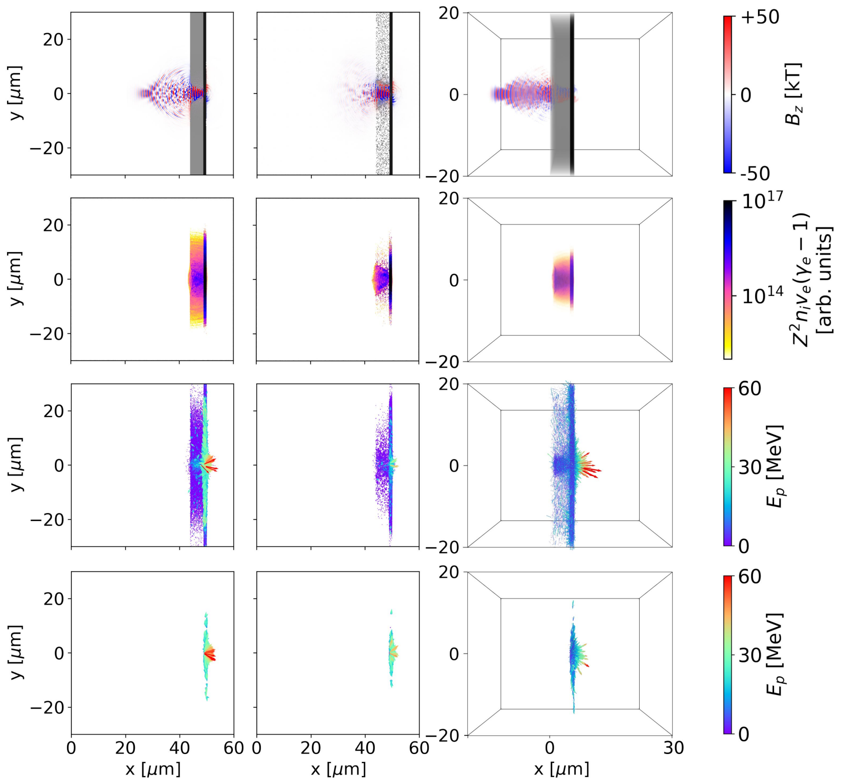
Simulation Parameters:

- Laser: a_0=20 (8.7x10^{20} W/cm^2), waist 3 µm, FWHM=30 fs
- Carbon foam, densities 2-**5**-10 **n$_c$**, lengths 2-**5**-10-15-20 **µm**
- Minimum Photon energy = 10 keV
- Substrate of 1 µm of Al → 2D 450 n$_c$ - 3D 80 n$_c$

↓ Not optimal for Bremsstrahlung

Formenti, A., Galbiati, M., & Passoni, M. (2022). Modeling and simulations of ultra-intense laser-driven bremsstrahlung with double-layer targets. Plasma Physics and Controlled Fusion, 64(4), 044009.

Foam Thickness 5 µm - Foam Density 5 n$_c$



Proportional to the emitted power

Photons as arrows from PIC

Photon as arrows from MC

Analytic estimations for Bremsstrahlung

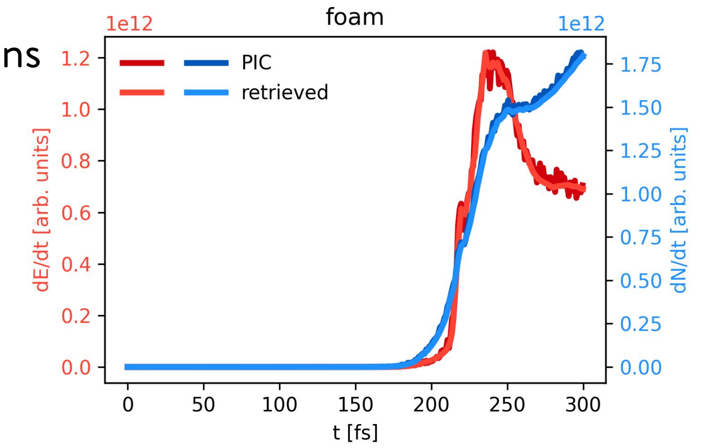
- Number and Power In emitted photons by foam and substrate electrons

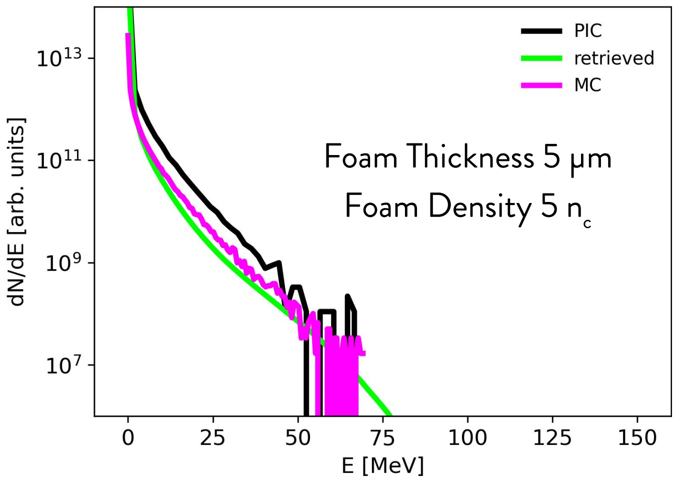
$$\frac{dE}{dt} = \sum_e n_i v_e w_e \int_{E_{p,min}}^{E_e} E_p \frac{d\sigma}{dE_p} dE_p$$

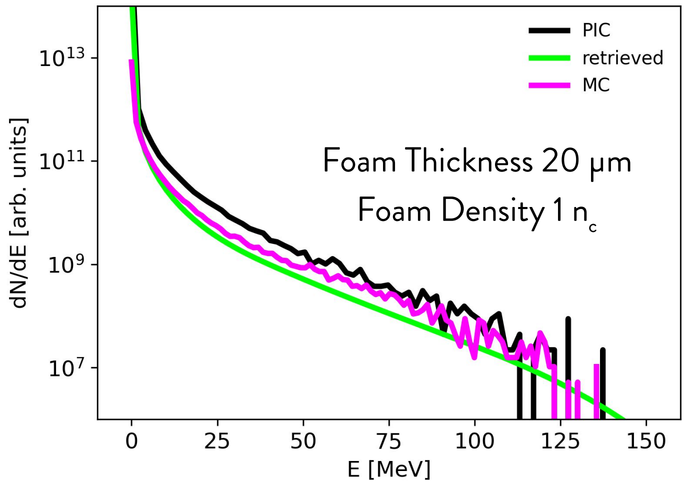
$$\frac{dN}{dt} = \sum_e n_i v_e w_e \int_{E_{p,min}}^{E_e} \frac{d\sigma}{dE_p} dE_p$$

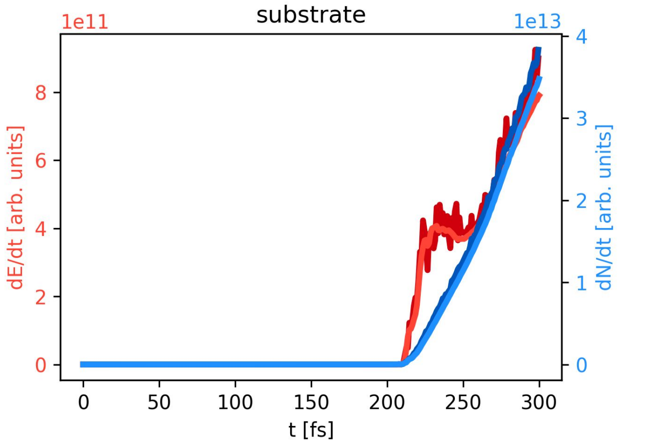
- Spectrum in energy of all emitted photons

$$\frac{dN_p}{dE_p} = (n_i t)_{sub} \int_{E_p}^{E_{e,max}} \frac{d\sigma}{dE_p} \frac{dN_e}{dE_e} dE_e$$







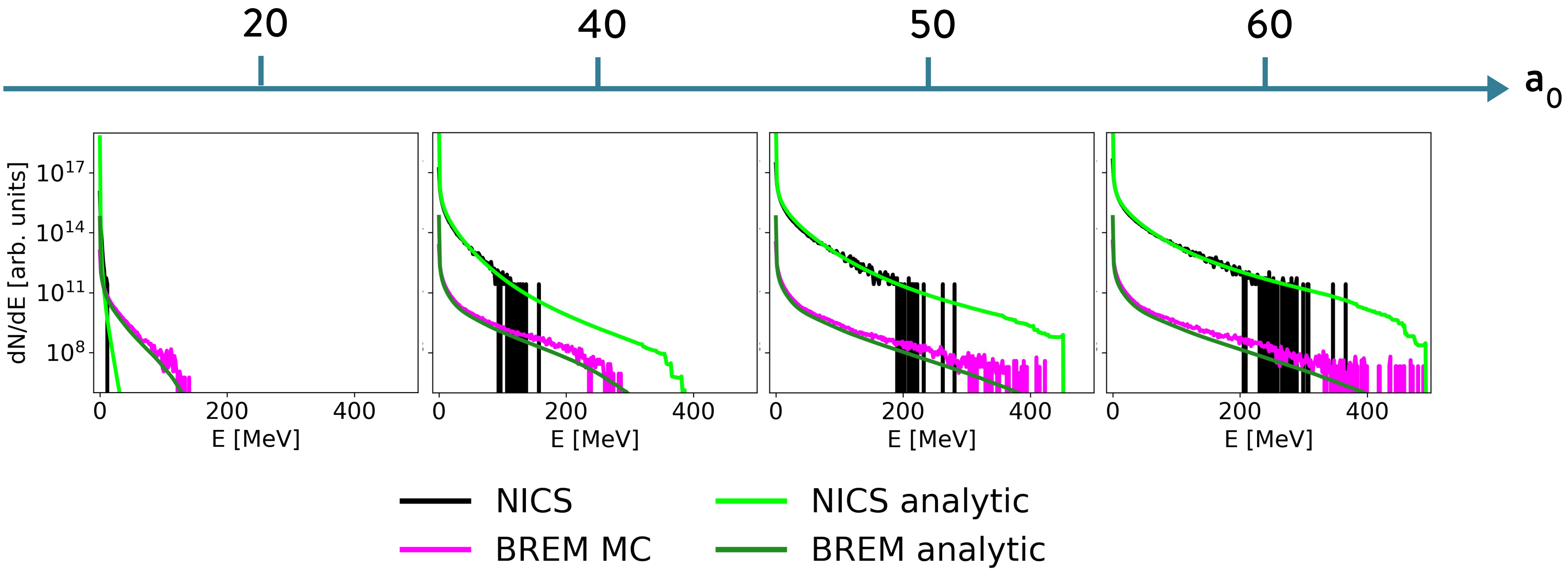


Bremsstrahlung vs NICS

Spectra in energy of all emitted Photons by Electrons

Foam Thickness 25 μm - Foam Density 1 n_c

Al Substrate Thickness 2 μm



Conclusions

NICS and Bremsstrahlung are both interesting for the development of

Tunable Laser-Driven High-Energy Photon Sources.

- DLTs can be **optimized** for emission changing target parameters.
- Complementary **analytical estimations** are available.
- **Complementary modelling strategies** for Bremsstrahlung with advantages and disadvantages.

Perspectives

- Use Smilei) for further investigations of NICS in DLTs (e.g. 3D)
- Development of Bremmstrahlung module in Smilei)
- Experiments!

Smilei)

3rd Smilei user & training workshop

9-11 March 2022

Questions? Ask now or contact me!

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